Fast luminance measurement method for asynchronous spiking pixels

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We present a new method to obtain a continuous and fast measurement of light intensity. It is targeted for Integrate and Fire (I&F) pixels that pulse with a frequency proportional to illumination. The procedure is intended to speed up the pixel readout of low illuminated pixels. It does not require synchronization of different digital signals, being compatible with continuous pixel operation. The method fundamentals are described in the letter. Experimental results validating the theory are provided.

Introduction: Luminance sensors with asynchronous spiking pixels are made up of pixels that pulse with a frequency proportional to illumination [1, 2, 3]. They have several inherent advantages over frame-based sensors: 1) Pixels operate continuously and there in not necessary to set an integration time; 2) Under average illumination conditions, pixel latency and power consumption are low; 3) Non illuminated pixels do not send any data off-chip, optimizing the bandwidth consumption. For these reasons, such sensors are suitable for specific applications that require good temporal resolution [4] or avoid reading out dark pixels [5].

In Fig. 1, the operation principle of an Integrate and Fire (I&F) pixel is depicted. Initially, the voltage at the integration capacitance, $V_c$, is reset. When the reset signal is disabled, the capacitor is discharged with a time constant $C \cdot \Delta V$, where $\Delta V$ is proportional to the excitation of the current source $I_{ph}$. The integration capacitance is dimensioned to obtain spiking frequencies in the order of milliseconds under average indoor conditions [6, 3]. Illumination levels are rendered by gauging the output frequency associated to each pixel.

Spiking sensors main disadvantage is slow operation under low illumination conditions. Since pixels spiking frequencies are proportional to illumination, pixel response can be very slow. That limits the sensor performance in low illuminated environments. To overcome this drawback, it is possible to increase globally the sensor sensitivity to light by increasing the comparator’s voltage threshold, $\Delta V$, as in Eq. 1, tuning the $V_{ref}$ voltage. Low $\Delta V$ values are suitable for low illuminated pixels. However, this traditional procedure has a negative impact with high illuminated pixels: increases their spiking rate, fixed-pattern-noise (FPN) and power consumption unnecessarily. Ideally, low values of $\Delta V$ should be set during a short time interval to measure the low illuminated regions with an acceptable latency.

We propose an alternative technique to speed up the pixel readout of low illuminated pixels without increasing significantly the sensor’s throughput, FPN and power consumption. The approach allows the measurement of pixel illumination values with a maximum latency time that can be set by the user and can be adapted dynamically depending on the minimum illumination value and the maximum output data flow required. Low values of $\Delta V$ are set during a short time interval just to speed up the response of low illuminated pixels.

Fig. 2 Proposed pixel readout method for low illuminated pixels. The comparator’s threshold voltage is sweep between its initial value, $V_{ref}(0)$, and a final one, $V_{ref,max}$, within a time interval, $T_{scan}$. As a result, pixel outputs can be readout earlier than keeping the initial voltage threshold constant.

Method description: Initially the pixel $V_{ref}$ voltage is set to $V_{ref}(0) = V_{ref0}$. We aim to speed up the pixel response in low illuminated regions without setting a constant low $\Delta V$ value. To do so, we propose to change the comparator’s threshold signal $V_{ref}$ dynamically, as is depicted in Fig. 2. Keeping the initial voltage threshold constant, would require an amount of time equal to $T_{scan}$ for the pixel readout. To expedite the pixel response, the signal that represents the transient voltage at the integration capacitance, $V_c(t)$, is modulated by the signal $V_{ref}(t) = a \cdot t + V_{ref0}$. Let us denote as $T_0, T_1, T_2, ..., T_n$ the different temporal values where $V_c(T_i) = V_{ref}(T_i)$, with $i = 0, 1, ..., n$, and the pixel fires. Our target is to determine them as a function of the photocurrent and the slope of the signal $V_{ref}(t)$. Assuming that $V_c(t) = V_{DD}$ and $V_{ref}(0) = V_{ref0}$, we can express both signals as follows:

$$V_c(t) = V_{DD} - \frac{I_{ph} \cdot t}{C}$$  \hspace{1cm} (2)

$$V_{ref}(t) = a \cdot t + V_{ref0}$$  \hspace{1cm} (3)

Using Equations 2 and 3, the first spike timestamp, $T_0$, and the voltage value $V_c(T_0) = V_{ref}(T_0)$ can be determined:

$$T_0 = \frac{V_{DD} - V_{ref0}}{a + \frac{I_{ph}}{C}}$$  \hspace{1cm} (4)

$$V_{ref}(T_0) = a \cdot T_0 + V_{ref0}$$  \hspace{1cm} (5)

Again, with Equations 2 and 3, and the values of $T_0$ and $V_{ref}(T_0)$, $T_1$ and $V_{ref}(T_1)$ can be computed:

$$T_1 = \frac{V_{DD} - V_{ref0}(T_0)}{a + \frac{I_{ph}}{C}}$$  \hspace{1cm} (6)

$$V_{ref}(T_1) = a \cdot (T_0 + T_1) + V_{ref0}$$  \hspace{1cm} (7)

Therefore, from the previous equations we can generalize and express $V_{ref}(T_n)$ and $T_n$, with $n > 1$, as follows:

$$V_{ref}(T_n) = a \cdot (T_0 + T_1 + ... + T_{n-1}) + V_{ref0}$$

$$T_n = \frac{V_{DD} - V_{ref}(T_{n-1})}{a + \frac{I_{ph}}{C}} = \frac{T_0 - a(T_0 + T_1 + ... + T_{n-1})}{a + \frac{I_{ph}}{C}}$$  \hspace{1cm} (8)

With $A = \frac{I_{ph}}{C}$. From Equation 8, a general expression of $T_n$ as a function of $T_0$ can be derived:

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**Fig. 1**: Top: Integrate & Fire pixel block diagram excluding the readout circuitry. Bottom: Transient voltage at the integration capacitance.
The voltage at the integration capacitance, $V_c(t)$, can be expressed as:

$$V_c(t) = V_{ref}(t) - \frac{T_n}{T_{n-1}}V_{ref,\text{max}} - \frac{T_n}{T_{n-1}}V_{ref,\text{f}}$$

In case the pixel illumination is not high enough to generate at least two events during $T_{scan}$, the pixel can be considered to be dark. The user can trade off between the number of events fired by the pixels and $T_{scan}$.

Experimental results: Fig. 3 displays the schematics of an I&F pixel implemented in the AMS HV 180nm standard fabrication technology. Digital readout logic is not shown. The pixel design allows full programmability of the voltages $V_{ref}$ and $V_{reset}$. A floating diffusion (FD) to store the value of $V_{reset}$ on pixel.

Fig. 3 Integrated I&F pixel schematics. Digital readout circuitry is excluded. Voltages $V_{ref}$ and $V_{reset}$ can be tuned independently. There is a floating diffusion (FD) to store the value of $V_{reset}$ on pixel.

should be noticed that when $V_{ref}(t)$ is decreasing the ratio between consecutive periods predicted by Equation 12 is inverted, i.e. $T_n/T_{n-1} \approx \frac{C}{T_p}$. Averaging different measured values of $T_n/T_{n-1}$, measurement errors can be significantly minimized.

Conclusion: A new procedure to speed up the measurement of the pixel illumination for I&F spiking pixels has been described and demonstrated. To accelerate the pixel response, we have proposed to change dynamically the pixel sensitivity to light varying the value of a pixel comparator threshold. Just two time intervals between consecutive spikes are necessary to measure pixel illumination. Lower illumination levels can be measured at the expense of increasing temporarily the pixel throughput. We intend to employ this method to readout pixels of low illuminated regions. To do so, circuitry to define an specific value for the voltage threshold within a certain group of pixels of a pixel array is being developed.

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